*Submission type: Research article*

**Generalist predators function as pest specialists: examining diet composition of spiders and ladybeetles across rice crop stages**

**Abstract**

1. Biocontrol, using natural enemies for pest control, has a long history in agriculture. It has received a surge of interest in the recent Anthropocene because of its potential as a valuable tool for sustainable agriculture.
2. To solve a long-standing puzzle in biocontrol—how well the ubiquitous generalist arthropod predators (GAPs) function as biocontrol agents—this study aimed to 1) quantify the diet composition of GAPs (spiders and ladybeetles) at different crop stages using stable isotope analysis, 2) examine the consistency of GAPs in pest consumption over years, and 3) investigate how abiotic and biotic factors affect pest consumption by GAPs.
3. Specifically, we sampled arthropod prey and GAPs in sub-tropical organic and conventional rice farms over crop stages (seedling, tillering, flowering, and ripening) in three consecutive years. Among our field-collected samples, 352 arthropod predator and 828 prey isotope samples were analyzed to infer predator-prey interactions.
4. Our results show the following: a) The proportion of rice pests in GAPs’ diets in both organic and conventional rice farms increased over the crop season, from 21-47% at the tillering stage to 80-97% at the ripening stage, across the three study years. The high percentage in pest consumption at late crop stages (flowering and ripening) suggests that GAPs can function as specialists in pest management during the critical period of crop production. Regarding individual predator groups, spiders and ladybeetles exhibited distinct dietary patterns over crop stages. b) The high pest consumption by GAPs at late crop stages was similar across years despite variable climatic conditions and prey availability, suggesting a consistency in GAP feeding habits and biocontrol value. c) The proportion of rice pests in GAPs’ diets varied with farm type and crop stage (e.g., higher in conventional farms and during flowering/ripening stages).
5. By quantifying the diet composition of GAPs over crop stages, farm types, and years, this study reveals that generalist predators have potential to produce a stable, predictable top-down effect on pests in rice agro-ecosystems. As sustainable agriculture has become increasingly important, incorporating the ubiquitous generalist predators into pest management will likely open a promising avenue towards this goal.

*Keywords: biocontrol, trophic interactions, generalist predators, rice paddy, organic and conventional farms, stable isotope analysis*

**1. Introduction**

Using natural arthropod enemies for pest control has a long history in agriculture. The earliest record of biocontrol was documented in the book *Plants of the Southern Regions* (*ca.* 304 A.D.): people sold ants and their nests in the markets to control citrus insect pests (Huang and Yang, 1987). While synthetic pesticides have become the main method for controlling pests in the past century, this comes at a cost, such as posing risks to people, reducing biodiversity and hampering ecosystem functions (Geiger *et al.*, 2010; Kehoe *et al.*, 2017). As agriculture has become the largest land use type worldwide and a major driver for the global biodiversity crisis in Anthropocene (Campbell *et al.*, 2017), a shift from synthetic pesticides to environmentally friendly practices (e.g., biocontrol) is urgently needed to make agriculture more sustainable (Gomiero *et al.*, 2011). For example, the European Commission has announced its plan to reduce the use of chemical pesticides in European Union agricultural systems by 50% by 2030 (European Commission, 2020). To achieve this ambitious sustainability goal, biocontrol by natural enemies has been considered a key approach and has regained importance in modern agriculture.

Natural enemies used for pest control can be classified into two major groups based on their prey range: specialist and generalist predators. While specialist predators (e.g., parasitoid wasps) have been widely advocated in agriculture because they target specific pest species and produce less undesirable non-target effects (Stiling and Cornelissen, 2005), generalist predators (e.g., spiders) have been increasingly appreciated for their conspicuous existence and consistent biocontrol effect on pests (Symondson *et al.*, 2002; Stiling and Cornelissen, 2005; Michalko *et al.*, 2019; Hsu *et al.*, 2021; Gajski *et al.*, 2023). For example, generalist predators were commonly reported in various agro-ecosystems and significantly reduced pest abundance in approximately 75% of cases in 181 field manipulative studies (Symondson *et al.*, 2002). Moreover, a meta-analysis suggests that generalist predators may exert stronger biocontrol effects on pest populations over time compared to specialists (Stiling and Cornelissen, 2005).

While the value of generalist predators has been increasingly appreciated, a few fundamental knowledge gaps need to be filled to validate their biocontrol potential and the underlying mechanisms in agro-ecosystems. For example, while studies have qualitatively analyzed the diets of generalist predators (e.g., using molecular gut content analysis to identify prey species) (Eitzinger and Traugott, 2011; Ingrao *et al.*, 2017; Albertini *et al.*, 2018), very few have quantified their diet composition over a growth season in the field (knowledge gap 1) (Hsu *et al.*, 2021; Otieno *et al.*, 2023). Quantifying their diet composition will help address the concern that generalist predators may switch their diet from pests to alternative prey and thus reduce their pest control effectiveness (Michalko *et al.*, 2019). For instance, if generalist predators still consume a high proportion of pests in their diet with the presence of alternative prey in the field, this result would help end a long debate on whether generalist predators serve well as biocontrol agents (Symondson *et al.*, 2002; Krey *et al.*, 2017; Michalko *et al.*, 2019). Moreover, examining the consistency of generalist predators in pest consumption in the field over years is important to assess the reliability of these predators as biocontrol agents in agriculture, although this information is lacking (knowledge gap 2). Given that temporal dynamics in population density or species composition commonly occur in agro-ecosystems (Settle *et al.*, 1996; Dominik *et al.*, 2018), a consistently high pest consumption by generalist predators over years, if it occurs, will provide strong support for applying these predators in pest management programs.

To understand the underlying mechanisms for the biocontrol effect of generalist predators, we also need to examine how various abiotic and biotic factors affect the diet composition of generalist predators in agro-ecosystems (knowledge gap 3). First, arthropod community composition (e.g., pest vs. alternative prey density) may vary with crop stages and affect predator-prey trophic interactions (Roubinet *et al.*, 2017). Therefore, we should examine how crop stage affects the pest consumption by generalist predators within a growth season. Second, we should examine whether farming practices (e.g., organic and conventional) influence the diet composition of predators (e.g., pest consumption) (Birkhofer *et al.*, 2011). This will demonstrate whether generalist predators provide varying biocontrol values in specific farm types. Third, we should investigate the relationship between the relative prey abundance and the diet composition of their predators. This will clarify whether pest abundance or predator preference mainly explains the pest consumption by predators (Wise *et al.*, 2006; Kuusk and Ekbom, 2012; Roubinet *et al.*, 2017; Eitzinger *et al.*, 2019). Lastly, we should examine how surrounding vegetation (e.g., forest cover) affects the diet composition of generalist predators. While surrounding vegetation reportedly affected arthropod diversity and predator-prey interactions in agro-ecosystems (Altieri and Letourneau, 1982; Altieri, 1999; Barbosa and Castellanos, 2005; Diehl *et al.*, 2013; Lichtenberg *et al.*, 2017), its effect on predators’ diet composition is unclear. Understanding this will provide insights for managing the agricultural landscape and promoting biocontrol services by generalist predators.

To address these three knowledge gaps, this study aimed to 1) quantify the diet composition of generalist predators, 2) examine the consistency of predators in pest consumption over years, and 3) investigate how abiotic and biotic factors may affect the diet composition of these predators. Filling these gaps will provide insights for applying generalist predators in biocontrol programs. Specifically, this study sampled arthropod prey and generalist arthropod predators (GAPs) in sub-tropical organic and conventional rice farms over the rice growth season (seedling, tillering, flowering, and ripening stages) in central Taiwan from 2017 to 2019, and quantified the diet composition of GAPs (ladybeetles and spiders) at each rice stage using stable isotope analysis (δ13C and δ15N). Although GAPs may consume various prey items, we expected that GAPs would consistently consume a high proportion of pests in their diet at late crop stages (with high pest densities) regardless of years. We also expected that the diet composition of GAPs would be affected by local abiotic and biotic factors (e.g., farm type, crop stage, percent forest cover, and the relative abundance of pests in the field). Stable isotope analysis has been widely applied in ecology to infer predator-prey trophic interactions and estimate the proportional contribution of different prey sources to predators’ diets (Post, 2002; Boecklen *et al.*, 2011; Layman *et al.*, 2012). This quantification method reflects accumulated prey consumption in predators’ diets, which may not be achieved by some “snap-shot” techniques (e.g., field observations and molecular gut content analysis) (Newton, 2016).

**2. Materials and Methods**

*2.1. Study system and sample collection*

We collected terrestrial arthropods in paired organic and conventional rice farms in subtropical Taiwan (120.656-120.721 °E; 24.364-24.489 °N) from 2017 to 2019 (three farm pairs in 2017 and seven farm pairs each in 2018 and 2019). While farms in the same pair were relatively close to each other (e.g., within a few hundred meters in distance), different farm pairs were at least 1 km apart from each other to reduce confounding effects. The study farms were 0.2 hectares on average and irrigated with surface water. The organic farms were managed with organic fertilizers (manure; 2-3 applications/crop season) and natural pesticides (tea saponins; 1 application/crop season during the seedling or tillering stage). The conventional farms were managed with synthetic nitrogen fertilizers (2-3 applications/crop season) and organophosphate pesticides (1 application/crop season during the tillering or flowering stage). At each major rice crop stage (seedling, tillering, flowering, and ripening stages) during the growing season (April - July) in each study year, we collected arthropod samples by sweep-netting (36 cm in diameter with a mesh size of 0.2 × 0.2 mm) the crop canopy 30 times in each of two transects inside a rice field. Each transect (ca 30 m long) was parallel to but 1.5m away from a randomly selected farm ridge. Samples were sealed in bags without chemical preservatives, iced, and transferred to refrigerator (−20ºC) in the laboratory. We identified and counted arthropods under a dissecting scope to the lowest possible taxonomic level (usually species, genus, or family). Main orders, families, and genera have been documented in a previous study by Hsu et al. (Hsu *et al.*, 2021).

*2.2. Stable isotope analysis of arthropod samples*

After identification, arthropod samples were prepared for stable isotope analysis. First, samples were oven dried (50ºC) for one week, ground, and weighed into individual tin capsules (5 × 9 mm). If necessary, several conspecifics would be pooled into a capsule to meet the minimum weight required for stable isotope analysis (i.e., 2 mg in this study). The number of isotope capsules for each species generally mirrored the arthropod community composition in the field. Stable isotope analysis (352 arthropod predator and 828 prey isotope samples) was conducted at the UC Davis Stable Isotope Facility using a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK). The standards for carbon and nitrogen stable isotope ratios were Vienna PeeDee Beleminte and atmospheric N2, respectively. The results of our samples were expressed in per mil (‰) relative to the international standards (δ13C and δ15N).

*2.3. Arthropod trophic guild assignment*

A trophic guild represents a group of species using similar resources and forms a basic component of food webs. The concept has been proved to be practical in current ecology because it condenses broad taxonomic information into distinct functional groups in communities (Blondel, 2003). In this study, we classified arthropod samples into four trophic guilds (one predator and three prey guilds): 1) “Predators” consisted of spiders and ladybeetles, which are the primary GAPs in rice farms. 2) “Rice herbivores” consisted of major rice pests, including planthoppers, leafhoppers, and stink bugs. 3) “Tourist herbivores” consisted of herbivorous species without direct trophic association with rice plants, including some grasshoppers and leaf beetles. 4) “Detritivores” consisted of arthropods that feed on decaying organic material or plankton, including various midge and fly species. The classification of prey guilds was based on a combination of literature surveys and k-means clustering of stable isotope signatures of arthropod samples (see Appendix A: Fig. S1 for a stable isotope biplot for the three prey sources). The arthropod families/genera in each trophic guild are detailed in Appendix A: Table S1. This study focused on the trophic interactions between generalist predators and their prey sources and therefore did not consider less abundant trophic guilds (e.g., parasitoids) in subsequent analyses.

*2.4. Data analyses*

To quantify the diet composition of predators, we constructed Bayesian stable isotope mixing models using the R MixSIAR package (Stock *et al.*, 2018) to estimate the proportions of different prey sources (i.e., the three prey guilds including rice herbivores, tourist herbivores, and detritivores) in predators’ diet. In the mixing models, individual farm-year combination and crop stage were included as fixed effects for predator isotope data; isotope data for the three prey guilds were pooled respectively to generate fixed source values because of their high mobility across farms (Mazzi and Dorn, 2012; Sun *et al.*, 2015). Isotope data at the seedling stage for the three study years were omitted from the analysis due to insufficient sample sizes for model estimation. To improve our model estimates, carbon and nitrogen concentration dependencies as well as the residual/process errors were incorporated (Phillips and Koch, 2002; Stock and Semmens, 2016). Trophic discrimination factors (TDFs) were estimated from the diet-dependent discrimination equation proposed by Caut *et al.* (2009). We ran three Markov Chain Monte Carlo (MCMC) chains, each with 50,000 iterations and a burn-in number of 25,000, along with a non-informative Dirichlet prior. Chain convergence was assessed via Gelman-Rubin and Geweke diagnostics. Bayesian posterior median estimates of diet composition (for each year-farm-stage combination) were extracted for further analyses. Bayesian posterior means, SDs, medians, and 95% credible intervals are provided in Appendix B.

To examine how local abiotic and biotic factors may affect the pest consumption by GAPs, we fit weighted generalized linear mixed models (GLMMs) with a beta distribution and a logit link function using the R glmmTMB package (Brooks *et al.*, 2017), with year, farm type, crop stage, percent forest cover, and the relative abundance of rice herbivores as fixed effects, farm ID nested within pair ID as random effects, and the proportion of rice herbivores consumed in predators’ diet as the response (i.e., posterior medians from the Bayesian stable isotope mixing models). Weights were computed based on the number of diet estimates in each year. Model parameters were estimated using maximum likelihood, and their significance was analyzed via Wald chi-square test using the “Anova” function in the R car package (Fox and Weisberg, 2018). Tukey’s post-hoc tests (α = 0.05) were performed for the significant factors using the “cld” function in the R emmeans package (Length, 2018). The percent forest cover around each study farm was estimated from Google Earth images by manually delimiting the forested areas within a 1-km radius circular buffer surrounding the farm and computing the fraction of these areas in the buffer zone. The 1-km radius was based on previous studies (Rusch et al., 2016; Karp *et al.*, 2018). Because spiders and ladybeetles may have different feeding behavior and preference, we also performed all the aforementioned analyses separately for each of the two predator groups. All analyses were conducted in R version 4.0.3 (R Core Team, 2021).

*2.5. Replication statement*

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| **Scale of inference** | **Scale at which the factor of interest is applied** | **Number of replicates at the appropriate scale** |
| Predator stable isotope analysis | Predator individuals collected at each rice stage in organic and conventional farms over three study years | 352 stable isotope samples (capsules) |
| Prey stable isotope analysis | Rice herbivore, tourist herbivore, and detritivore individuals collected at each rice stage in organic and conventional farms over three study years | 828 stable isotope samples (capsules) |

*2.6. Ethics statement*

Ethical approval was not required for this study.

**3. Results**

*3.1. Diet composition of predators in rice farms*

Across organic and conventional rice farms during 2017-2019, the proportion of rice herbivores in predators’ diet increased over the course of the crop season from 21-47% at the tillering stage to 80-97% at the ripening stage; the proportion of detritivores in predators’ diet decreased from 35-61% at the tillering stage to <1% at the ripening stage; the proportion of tourist herbivores in predators’ diet also decreased from 13-20% at the tillering stage to 3-18% at the ripening stage (Fig. 1a; Appendix A: Table S2, Fig. S2).

Regarding individual predator groups, spiders and ladybeetles showed a marked difference in their diet composition over crop stages during 2017-2019. Across organic and conventional farms, spiders consumed a higher proportion of detritivores (31-55%) in their diet in the beginning of crop season (tillering stage) and substantially increased the consumption on rice herbivores to 78-95% in late crop season (ripening stage) (Fig. 1b; Appendix A: Table S2, Fig. S2). In contrast, ladybeetles in both organic and conventional farms consumed a low proportion of detritivores (≤ 8%) and a steadily high proportion of rice herbivores (≥ 80%) in their diet throughout the crop season (Fig. 1c; Appendix A: Table S2, Fig. S2). Tourist herbivores generally did not constitute an important prey source and contributed less than 33% to the diet of spiders and ladybeetles (Fig. 1b, 1c; Appendix A: Table S2, Fig. S2).

*3.2. Patterns of rice herbivore consumption by predators*

We further analyzed rice herbivore consumption by GAPs since these herbivores are the main pests of concern. The patterns of rice herbivore consumption by both predators in organic and conventional rice farms were generally similar across the three study years, suggesting consistency in GAPs’ feeding habits (Fig. 2). Interestingly, spiders and ladybeetles exhibited distinct within-season patterns of rice herbivore consumption. For spiders in organic and conventional farms, the proportion of rice herbivores in their diet increased toward later crop season, ranging from 17-48% (tillering) to 78-95% (ripening) (Fig. 2b; Appendix A: Table S2, Fig. S2), whereas for ladybeetles in organic and conventional farms, the proportion of rice herbivores in their diet remained relatively stable throughout the season, ranging from 80-93% (tillering) to 97-98% (ripening) (Fig. 2c; Appendix A: Table S2, Fig. S2).

*3.3. Factors associated with rice herbivore consumption by predators*

The proportion of rice herbivores in GAPs’ diet differed between organic and conventional farms for both predators (*χ*2 = 7.92, *P* = 0.01) and spiders(*χ*2 = 4.93, *P* = 0.03), but not ladybeetles (*χ*2 = 0.47, *P* = 0.49; Table 1). Specifically, both predators consumed a higher proportion of rice herbivores in their diet in conventional vs. organic farms (Table 2). The proportion of rice herbivores in GAPs’ diet also differed among crop stages (both predators: *χ*2 = 249.84, *P* < 0.001; spiders: *χ*2 = 119.01, *P* < 0.001; ladybeetles: *χ*2 = 184.32, *P* < 0.001; Table 1). Specifically, GAPs consumed higher proportions of rice herbivores in their diet at the flowering and/or ripening stage vs. the tillering stage (Table 3).

The proportion of rice herbivores consumed in GAPs’ diet was not associated with the percent forest cover within a 1-km radius buffer surrounding the study farms (both predators: *χ*2 = 0.06, *P* = 0.80; spiders: *χ*2 = 0.12, *P* = 0.73; ladybeetles: *χ*2 = 0.34, *P* = 0.56; Table 1). Furthermore, the proportion of rice herbivores consumed was not associated with the relative abundance of rice herbivores in the field (both predators: *χ*2 = 0.56, *P* = 0.46; spiders: *χ*2 = 0.58, *P* = 0.45; ladybeetles: *χ*2 = 0.38, *P* = 0.54; Table 1).

**4. Discussion**

Because the worldwide demand for environmentally friendly practices in agriculture has increased, we investigated the potential of GAPs (ubiquitous in nature) as biocontrol agents in rice agro-ecosystems. Specifically, we used stable isotopes to quantify the diet composition of GAPs in organic and conventional rice farms during the crop season in three consecutive years. Our main results include the following: 1) Across the three study years, the rice herbivore consumption by GAPs increased in both organic and conventional farms over the crop season, from 20-47% at the tillering stage to 80-97% at the ripening stage. The high percentage at the ripening stage indicates that GAPs could function as pest specialists during critical growth (late crop) stages. Notably, rice herbivore consumption by spiders increased gradually toward the later crop season, whereas the consumption by ladybeetles remained stable throughout the season. 2) Our results revealed similar among-year patterns in rice herbivore consumption by GAPs in organic and conventional rice farms, suggesting a consistency in GAPs’ feeding habits and biocontrol value. 3) The proportion of rice herbivores in GAPs’ diets varied with farm type and crop stage (e.g., higher in conventional farms and during flowering/ripening stages). However, contrary to results from previous studies, pest consumption by GAPs was not associated with percent forest cover or the relative abundance of rice herbivores in the field. We discuss in the following: 1) GAPs function as pest specialists at late crop stages, 2) GAPs exhibit consistent pest consumption patterns over years, 3) factors associated with pest consumption by GAPs, and 4) the potential caveats of this study (e.g., pest suppression and intraguild predation). We finish by highlighting the implications of our results for agricultural management.

*4.1. Generalist predators function as pest specialists at late crop stages*

While biocontrol, a farming practice with a long history, offers a promising solution for sustainable agriculture, the use of GAPs as biocontrol agents remains a concern because GAPs may switch diets between pests and alternative prey (Albajes and Alomar, 1999; Prasad and Snyder, 2006; Roubinet *et al.*, 2018). This study addressed this concern and revealed a consistency in high pest consumption by GAPs at late crop stages over years. The results provide not only strong support for using GAPs in sustainable pest management, but also a novel aspect in biocontrol—generalist predators may function as guild-level specialist predators of pests during the late crop season. Specifically, across the three study years, GAPs in both organic and conventional farms consumed an increasing proportion of rice herbivores over the crop season, reaching 80-97% in predators’ diet at the ripening stage, whereas the proportions of alternative prey (detritivores and tourist herbivores) in their diet gradually decreased below 18% at the ripening stage (Fig. 1; Appendix A: Table S2, Fig. S2). The increase in rice herbivore consumption over time suggests that the biocontrol potential of predators increases toward late crop stages and peaks at the critical stage of crop production. This could be because of a higher herbivore (pest) density at late crop stages, suggested by a correlation between rice herbivore consumption and crop stage (see *Factors associated with pest consumption by predators*).

While GAPs consumed a high proportion of pests at late crop stages, the two major predator groups in our study system, spiders and ladybeetles (Table S1), exhibited distinct dietary patterns over the crop season. Specifically, pest consumption by spiders increased substantially, but pest consumption by ladybeetles remained stable over the season (Fig. 2b vs. 2c). This may be because different foraging modes—sit-and-wait (spiders) or actively hunting (ladybeetles)—can lead to different prey capture and thus diet composition (Nyffeler, 1999; Klecka and Boukal, 2013). For example, long-jawed orb-weavers (*Tetragnatha*), the most abundant genus in our spider samples, are sit-and-wait predators. The diet composition of these predators generally reflects prey availability (Nyffeler, 1999). In contrast, ladybeetles are actively hunting predators and may preferentially feed on rice herbivores, resulting in stable pest consumption over time. Because predator foraging modes shape predator-prey-plant interactions (Schmitz, 2008), we encourage future studies to examine different assemblages of sit-and-wait vs. actively hunting predators in field conditions to reveal the most efficient biocontrol practice over the entire crop season.

*4.2. Generalists exhibit consistent pest consumption patterns over years*

Ideal biocontrol agents provide a consistent, predictable effect on pests under various environmental conditions. Accordingly, GAPs in this study showed consistent pest consumption across years, despite various abiotic and biotic environmental conditions. Specifically, regarding the abiotic factors, the daily mean temperature, particularly from April to June, varied substantially among years (Appendix A: Fig. S3). The daily precipitation also fluctuated over the three study years, with multiple high precipitation events in 2017, overall low precipitation in 2018, and relatively uniform precipitation in 2019 (Appendix A: Fig. S3). Regarding the biotic factors, the composition of rice herbivores at the flowering and ripening stages differed substantially among the three years, in particular the two most dominant groups: leafhoppers (Cicadellidae/*Nephotettix*) and planthoppers (Delphacidae/*Nilaparvata*) (Appendix A: Table S3). Although both abiotic and biotic factors varied substantially over the years of our study, pest consumption by GAPs generally remained stable, suggesting that GAPs can be a predictable, valuable tool for pest control in sustainable agriculture (but see Eitzinger *et al.*, 2021).

*4.3. Factors associated with pest consumption by predators*

The proportion of rice pests in GAPs’ diets differed between farm types and among crop stages but was not associated with the percent forest cover surrounding the farms or the relative abundance of rice herbivores in the field. Overall, GAPs in conventional farms consumed a higher proportion of rice pests in their diet compared to those in organic farms. There are two explanations for this: 1) Organic farming may promote arthropod diversity and therefore distract predators from feeding on target pests (Bengtsson *et al.*, 2005; Birkhofer *et al.*, 2008; Lichtenberg *et al.*, 2017). 2) Pest densities may be higher in conventional farms (Porcel *et al.*, 2018), leading to higher predator-prey encounter rates and thus pest consumption by GAPs. Regardless of the potential mechanisms, our results highlight the important but overlooked biocontrol value of GAPs in conventional farming systems.

Besides farming practices, crop stages also affected pest consumption. Overall, pest consumption by GAPs increased from early (tillering) to late (ripening) stages, consistent with previous studies where predators consumed more pests in the late crop season (Roubinet *et al.*, 2017; Hsu *et al.*, 2021). This may be because pest populations increased with rice development and eventually predominated, leading to high pest consumption by GAPs at the flowering and ripening stages. These findings indicate a higher biocontrol value of predators when the crop production is most vulnerable to pest damage. Therefore, farming practitioners may want to avoid practices that harm predators (e.g., chemical applications) during this period to maintain healthy predator populations and associated ecosystem services.

Complex habitat structure (e.g., surrounding vegetation) has been suggested to promote predator abundance and diversity (Langellotto and Denno, 2004; Diehl *et al.*, 2013), but such higher complexity did not affect predators’ diet composition in our study. This might be because the prey species in our study system were mostly associated with rice plants but not the surrounding vegetation, consistent with a meta-analysis where habitat complexity had no effect on crop herbivore densities (Langellotto and Denno, 2004). Furthermore, although the diet composition of generalist predators may correlate with prey availability in the field (Wise *et al.*, 2006; Hsu *et al.*, 2021), our beta regression models suggest no such correlation between rice herbivores and GAPs. An explanation is that the relative abundance of rice herbivores was highly correlated with crop stage, a significant factor likely associated with various covariates (e.g., rice plant height) and explaining most variations in pest consumption by GAPs . We encourage further experiments, both observational and manipulative, to clarify the link between prey availability and generalist predators’ diet composition in the field.

*4.4. Potential caveats of this study*

Our study demonstrates high pest consumption by GAPs in rice fields over three years and examines the factors influencing GAPs’ diet composition. While our study provides evidence for GAPs’ biocontrol potential, some caveats may exist. First, high pest consumption in GAPs’ diets does not necessarily imply a strong suppression of pest populations in the field, since pest population dynamics depend not only on the per capita effect of predators but also predator density and diversity (Letourneau *et al.*, 2009; Rusch *et al.*, 2016). To unveil the connection between per capita pest consumption and overall pest dynamics, future work may require complementing stable isotope analysis with field observations of predator and pest populations. Furthermore, future work may examine crop damage and production to reveal the effect of GAPs on pest control and crop performance. Second, while intra-guild predation potentially influences the pest control by GAPs (Straub *et al.*, 2008; Michalko *et al.*, 2019), it was not quantified in our diet composition analysis due to the limitation of stable isotope mixing models (Hsu *et al.*, 2021). However, this may not be a major concern in our study because rice plants grow in dense clumps and form a complex structure that could substantially relax intra-guild predation pressure (Finke and Denno, 2006; Janssen *et al.*, 2007). Regardless, we caution that our diet estimates of predators (without predator-predator interference) might not apply to systems where intra-guild predation prevails.

**5. Conclusions**

While biocontrol has been recognized as a valuable tool for sustainable agriculture, whether generalist predators can serve as effective biocontrol agents in pest management remains unclear. Our study helps solve this long-standing puzzle by using stable isotope analysis to quantify the diet composition of GAPs (spiders and ladybeetles) over the rice growth season and identifying the underlying mechanisms for enemy-pest interactions in rice farms over three consecutive years. The results show a high proportion of rice pests in GAPs’ diets in both organic and conventional rice farms (e.g., 80-97% at the ripening stage), suggesting that these generalist predators function as “pest specialists” at late crop stages (when rice plants are fruiting and pests are abundant). The high pest consumption remained consistent across years regardless of abiotic and biotic conditions, demonstrating the potential that generalist predators may produce a stable, predictable top-down effect on pests. Overall, our study lends support to applying generalist predators as biocontrol agents in both organic and conventional rice farms. As sustainable agriculture has become more important than ever in human history, incorporating the ubiquitous generalist predators into pest management, such as maintaining healthy populations of these predators, will likely open a promising avenue towards this goal.

**Appendix A and B. Supporting information**

Supplementary information associated with this article can be found in the online version at doi:xxx.

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**Tables with captions**

**Table 1.** Statistical results from GLMM beta regression models for examining the effects of abiotic and biotic factors on pest consumption by spiders, ladybeetles, and both predators.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Model | Factor | *d.f.* | *χ*2 | *P* |
| Both predators | Year | 2 | 8.00 | 0.02 |
|  | Farm type | 1 | 7.29 | 0.01 |
|  | Crop stage | 2 | 249.84 | < 0.001 |
|  | Percent forest cover | 1 | 0.06 | 0.80 |
|  | Relative abundance of rice herbivores | 1 | 0.56 | 0.46 |
| Spiders | Year | 2 | 9.30 | 0.01 |
|  | Farm type | 1 | 4.93 | 0.03 |
|  | Crop stage | 2 | 119.01 | < 0.001 |
|  | Percent forest cover | 1 | 0.12 | 0.73 |
|  | Relative abundance of rice herbivores | 1 | 0.58 | 0.45 |
| Ladybeetles | Year | 2 | 17.29 | < 0.001 |
|  | Farm type | 1 | 0.47 | 0.49 |
|  | Crop stage | 2 | 184.32 | < 0.001 |
|  | Percent forest cover | 1 | 0.34 | 0.56 |
|  | Relative abundance of rice herbivores | 1 | 0.38 | 0.54 |

**Table 2.** Tukey’s post-hoc tests comparing the proportion of rice herbivores consumed in the diet of predators in organic and conventional rice farms. Different superscript letters indicate significant differences in the estimated marginal means (EMMs) of the posterior medians from Bayesian stable isotope mixing models (α = 0.05).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Model | Farm type | EMMs (± SE) | Lower 2.5% | Upper 2.5% |
| Both predators | Organic | 0.61a (±0.08) | 0.45 | 0.76 |
|  | Conventional | 0.81b (±0.05) | 0.69 | 0.90 |
| Spiders | Organic | 0.55a (±0.10) | 0.35 | 0.73 |
|  | Conventional | 0.79b (±0.07) | 0.63 | 0.90 |
| Ladybeetles | Organic | 0.95a (±0.01) | 0.93 | 0.96 |
|  | Conventional | 0.95a (±0.01) | 0.94 | 0.96 |

**Table 3.** Tukey’s post-hoc tests comparing the proportion of rice herbivores consumed in the diet of predators at three crop stages (tillering, flowering, and ripening stages). Different superscript letters indicate significant differences in the estimated marginal means (EMMs) of the posterior medians from Bayesian stable isotope mixing models (α = 0.05).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Model | Crop stage | EMMs (± SE) | Lower 2.5% | Upper 2.5% |
| Both predators | Tillering | 0.24a (±0.06) | 0.14 | 0.36 |
|  | Flowering | 0.85b (±0.04) | 0.76 | 0.91 |
|  | Ripening | 0.91c (±0.03) | 0.85 | 0.95 |
| Spiders | Tillering | 0.27a (±0.07) | 0.16 | 0.43 |
|  | Flowering | 0.81b (±0.05) | 0.69 | 0.89 |
|  | Ripening | 0.86b (±0.04) | 0.75 | 0.93 |
| Ladybeetles | Tillering | 0.92a (±0.01) | 0.89 | 0.93 |
|  | Flowering | 0.92a (±0.01) | 0.90 | 0.93 |
|  | Ripening | 0.98b (±0.01) | 0.98 | 0.99 |

**Figures**

**Figure 1.** The proportions (mean ± SE) of prey sources (rice herbivores, tourist herbivores, and detritivores) consumed in the diet of (a) both predators, (b) spiders, and (c) ladybeetles in organic and conventional rice farms over crop stages. The proportions were computed from the Bayesian posterior medians of diet estimates in replicate farms over the three study years.

**Figure 2.** The proportion of rice herbivores consumed in the diet of (a) both predators, (b) spiders, and (c) ladybeetles in organic and conventional rice farms over crop stages in the three study years. The proportions were computed from the Bayesian posterior medians of diet estimates in replicate farms.

**Figure 3.** The relative abundance of prey sources in organic and conventional rice farms over crop stages during the three study years. The relative abundance was determined from the sweep-net samples pooled across replicate farms.

**Figure 1.**

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**Figure 2.**

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**Figure 3.**

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